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Two-Copy Wavelength Conversion of an 80 Gbit/s Serial Data Signal Using Cross-Phase Modulation in a Silicon Nanowire and Detailed Pump-Probe Characterisation

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Abstract *We experimentally demonstrate 80 Gbit/s wavelength conversion to two copies by simultaneously extracting the blue- and red-shifted sidebands from XPM in a silicon nanowire. Bit error rates of 10^{-9} with only ~2 dB power penalty is achieved for both sidebands. Detailed pump-probe characterisation reveals amplitude and phase responses.*

Introduction

Silicon based optical signal processing has attracted considerable research interest in recent years, due to its complementary metal-oxide-semiconductor (CMOS) compatibility, low cost, ultra-compactness, integration potential with electronics, ultra-broad bandwidth and ultra-high-speed operation[1]. Demonstrations have largely focused on four-wave mixing (FWM), where dispersion engineering has enabled efficient conversion efficiency in spite of the detrimental two-photon absorption (TPA) and free carrier absorption (FCA). In fact, it has been shown that the TPA/FCA slow recovery dynamics do not have an impact on the FWM speed[2] and FWM-based all-optical wavelength conversion (AOWC) up to 640 Gbit/s has been demonstrated[3]. However, the slow carrier recovery turns out to be beneficial for fast chirping effects by cross-phase modulation (XPM). Unlike semiconductor optical amplifiers (SOAs), the XPM-mediated chirp turns out to be equally fast on the red and the blue side for XPM in silicon waveguides.

In this paper, we present detailed pump-probe characterisations revealing the amplitude and phase response of XPM in silicon nanowires. The measured dynamics show that the red and blue shift is of similar order of magnitude and speed for the parameters used, and we propose to exploit this to realize two-copy wavelength conversion by extracting the red- and blue-shifted sidebands simultaneously. We demonstrate successful two-copy XPM wavelength conversion at 80 Gbit/s with similar performance.

Dynamical measurement of silicon nanowire

The silicon nanowire used for wavelength conversion is 8 mm long and has a 450 nm width and 250 nm height. The intensity and phase dynamics of the silicon nanowire is measured using a terahertz optical asymmetric demultiplexer (TOAD)-based pump-probe scheme as described in reference[4]. The pump and probe are pulses with 5 ps pulse width having repetition rate of 665 MHz. The central wavelengths of pump and probe are 1555 nm and 1540 nm, respectively. Fig. 1(a) shows the measured intensity and phase response. The amplitude response has two components. The

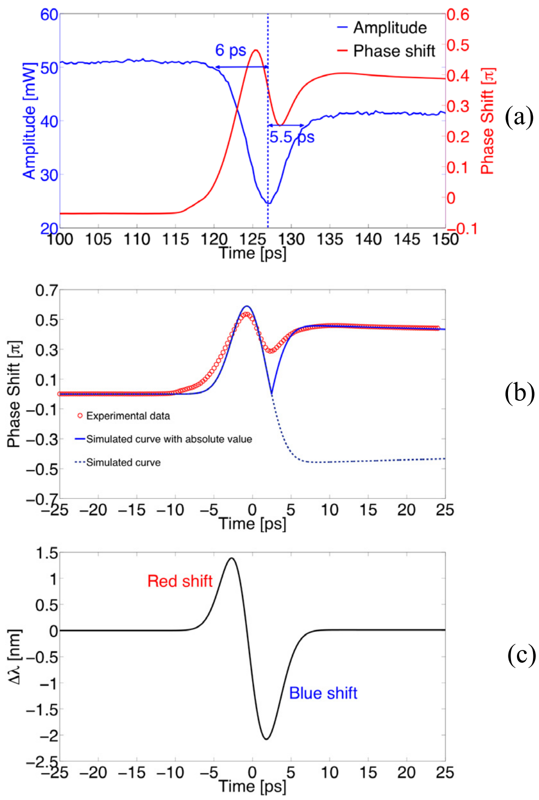

Fig. 1: (a) Measured Amplitude and phase response using TOAD loop (b) Fitted phase shift curve (c) Simulated wavelength chirp based on the TOAD measurement.

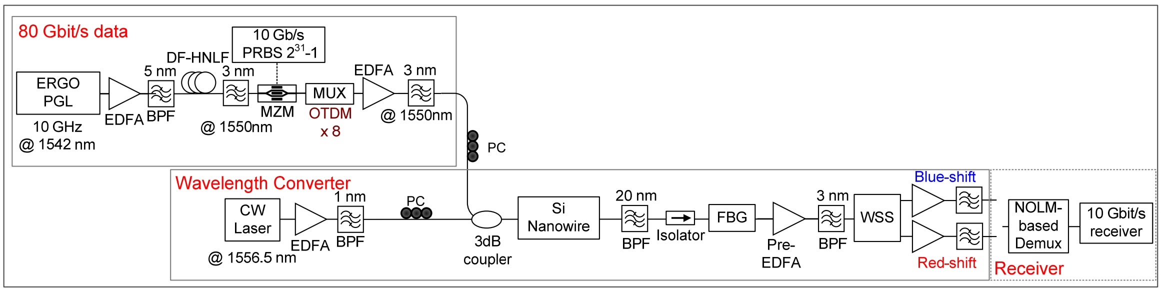

Fig. 2: Experimental scheme of Silicon nanowire based wavelength conversion

first part of the response is an ultra-fast absorption feature, whose duration is pulse-width limited, which we associate with TPA of pump and probe pulses. The second part is a slow recovery tail due to the long lifetime of free carriers in silicon, which in this case are generated by TPA. The measured phase response is positive at all times because the TOAD setup measures the absolute value of the phase. We use a simple model[5], taking into account the Kerr effect, TPA and free carrier effects, to analyze the experimental curve. The simulated phase response (blue solid curve) is compared to the experimental data (red dotted curve) in Fig. 1(b). The experimental data from the TOAD setup contains a further convolution with the probe pulse (source of the finite temporal resolution of the TOAD), and as a result, several features in the experimental data are broadened with respect to the simulated data. This is why the initial phase response is slightly smaller, and broader, in the experimental data. By taking the negative differential with respect to time of the simulated (dotted blue) phase shift curve of Fig. 1(b), we obtain the wavelength chirp shown in Fig. 1(c). A fast red-shift and a blue-shift, both of somewhat shorter duration than the pump pulse, are clearly observed at the front edge and tail of the pump pulse (central at time=0). Moreover, the blue-shift is slightly stronger than the red-shift, this magnitude difference being determined by the number of accumulated free carriers.

Experimental setup

The experimental setup for XPM-based wavelength conversion in a silicon nanowire is shown in Fig. 2. The 80 Gbit/s serial data signal is generated using the Optical Time Division Multiplexing (OTDM) technique. An erbium glass oscillator (ERGO) optical pulse source generates a 10 GHz pulse train at 1542 nm with 2 ps FWHM. A pulse compression stage is utilized, where after amplification in an EDFA, the 10 GHz pulse train is sent into a dispersion flattened highly nonlinear fiber (DF-HNLF) to broaden the spectrum. The output spectrum is filtered at 1550 nm using a 3 nm bandpass filter. Then, a Mach-Zehnder modulator encodes a 10 Gbit/s on-off keying (OOK) data sequence (PRBS 2^{31}-1) on the pulse train and the 10 Gbit/s data signal is multiplexed to 80 Gbit/s by a passive fiber delay and polarization maintaining multiplexer (MUX). The 80 Gbit/s OTDM OOK data signal is amplified by a high power EDFA and the average signal power coupled into the silicon nanowire is 16.5 dBm. The pulse width of the data signal is measured to 1.7 ps using an autocorrelator, which implies a peak power of 25.2 dBm. A continuous wave (cw) probe at the wavelength of 1556.5 nm is amplified, bandpass-filtered, and sent into the silicon nanowire together with the 80 Gbit/s data signal. The power of the cw probe coupled into the silicon nanowire is 15.5 dBm. The polarization states into the silicon nanowire of the data signal and the cw probe are both aligned to the TE mode of the nanowire using polarization controllers. After the silicon

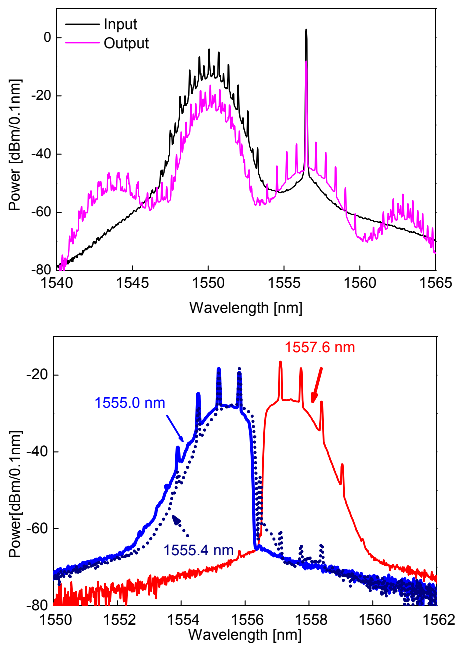

Fig. 3: (upper) Spectra measured at input and output of the silicon nanowire (lower) Extracted spectra from both blue-shift and red-shift sidebands

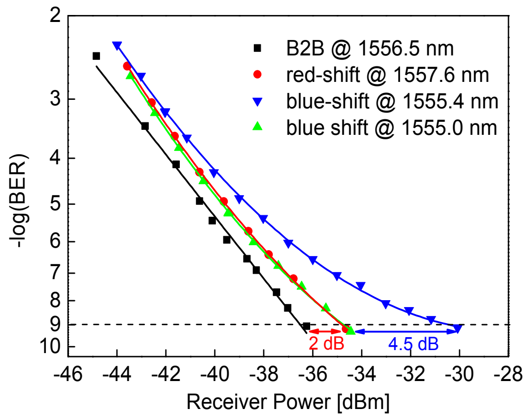

Fig. 4: BER performance

nanowire where the XPM occurs, a bandpass filter with 20 nm bandwidth is used to partly suppress the original data. Two fiber Bragg gratings with a central wavelength at 1556.5 nm and 0.8 nm bandwidth are used to suppress the cw carrier. A wavelength selective switch (WSS) is used to simultaneously extract both the high-frequency (blue) and low-frequency (red) sidebands on the probe output. The filtered output signal is sent into a nonlinear optical loop mirror (NOLM) for demultiplexing the converted 80 Gbit/s data signal to a 10 Gbit/s channel, followed by detection in a 10 Gbit/s pre-amplified receiver. The bit error rate (BER) performance is measured for both the back-to-back data signal and the wavelength-converted signals.

Experimental results and discussion

Fig. 3 (upper) shows the spectra measured at input and output of the Silicon nanowire, respectively. At the output of the Silicon nanowire, the cw probe is spectrally broadened due to the XPM caused by the co-propagating data signal in the silicon nanowire. The 80 GHz components are clearly seen in the sidebands of the cw probe. As shown in Fig. 3 (lower), the sidebands that include the information of the original data signal are extracted by WSS filtering at 1557.6 nm (red-shift), and at 1555.4 nm and 1555.0 nm (blue-shift). The WSS filters are Gaussian bandpass filters with bandwidths of 2 nm. The measured BER performances as a function of received power are shown in Fig. 4. The converted data signals at 1555.4 nm (blue-shift side) and 1557.6 nm (red-shift side) are extracted, and these signals have equal wavelength separation from the carrier at 1556.5 nm. As shown in Fig. 4, both signals achieve BER of 10^{-9}. Compared to the red-shift side, results for the blue-shift side show an obvious error floor with an additional 4.5 dB penalty, which gives a 6.5 dB total penalty compared to the back-to-back (B2B) data signal. However, if we extract the blue-shift side data slightly further away from the carrier (filter at 1555.0 nm), the BER performance of the converted signal achieves notable improvement and has a performance similar to the red-shift side (filter at 1557.6 nm). These results agree with the previous analysis, demonstrating that the wavelength chirp on the blue side is slightly higher compared to the red side due to the accumulation of free carriers.

The converted data signals at 1557.6 nm and 1555.0 nm both have ~2 dB penalty with respect to the B2B data signal. We believe that this penalty is mainly caused by the lower optical signal noise ratio (OSNR) after going through the silicon nanowire, which has a relatively high insertion loss of ~6.6 dB including the coupling and propagation loss.

Conclusions

We have experimentally demonstrated 80 Gbit/s wavelength conversion to two copies by simultaneously extracting the blue- and red-shifted sidebands after XPM in a silicon nanowire. BERs of 10^{-9} are measured for both sidebands, with a receiver sensitivity penalty of ~2 dB. We observe that in order to obtain equal performance between the two converted signals, the blue-shifted filter must be shifted further away from the carrier compared to the red-shifted filter. This result is consistent with the nanowire characterisation using a TOAD loop, where we found that the magnitude of the blue frequency chirp is slightly higher than the red chirp.

Acknowledgements

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